

Calibration of the GeoSAR Dual Frequency Interferometric SAR

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Outline

- Review of relevant system parameters for the GeoSAR airborne SAR system and system status.
- List parameters to calibrate.
- Present general method used for calibration.
- Discuss calibration sites.
- Show an example of our procedure for calibration.

Two related talks at this Workshop:

- “Phase Screen Determination for the GeoSAR Interferometric Mapping Instrument” in the Wednesday SAR Processing Session at 9:40.
- Poster titled “Baseline Calibration of the GeoSAR Interferometric Mapping Instrument”.

Description of GeoSAR Airborne SAR System

- Radar is installed on a Gulfstream II business jet.
- The system simultaneously maps swaths on both sides of the aircraft at two frequencies, X-Band and P-Band.
- At P-Band, data is collected for two interferometric baselines and at the crossed polarization.
- At X-Band, data is collected for one of two possible interferometric baselines at a single polarization.
- Data collected at one of two operational bandwidths, 80 or 160 MHz.
- Aircraft position and attitude are measured with two Honeywell Embedded GPS Inertial Navigation Units (EGI) and an Ashtech Z12 GPS receiver.
- The mechanical orientation and position of the antennas is actively measured by a Laser Baseline Metrology System (LBMS).

GeoSAR Status

- GeoSAR system has flown six engineering checkout flights. We have collected X-Band data over calibration sites and targets of opportunity in Southern California.
- Because of difficulties with frequency allocations, we have been unable to transmit using the P-Band system over land.
- We have collected no LBMS data yet. The LBMS is in final testing and calibration prior to integration on the aircraft.

GeoSAR Processing Flow

- On board the plane, platform motion and attitude data along with a minimal set of information about the radar are written on to an optical disk. Full headers and raw range line data are written to tape.
- Data from the optical disk are optimally blended with differential GPS data by the Motion Measurement Preprocessor (MMP). The MMP creates the necessary input files for further processing.
- Range line data is transferred from the tape to disk and processed through the Interferometric Processor (IP).

Use of Calibration Parameters

Parameter	User			Source			
	ARC	MMP	IP	mcal	icf	rcf	adp
Fiducial Measurements	X	X		X			X
Phase Screen			X		X		
EGI Biases			X		X		
Baseline Correction		X			X		
Common Range Delay			X		X		
Differential Time Delay			X		X		
Phase Correction			X		X	X	
Amplitude Correction			X			X	

Parameters to be Estimated

- Four common range delays: UHF right looking, UHF left looking, X right looking, and X left looking.
- Ten differential time delays: UHF right single transmit, UHF right ping-pong, UHF right cross pole, UHF left single transmit, UHF left ping-pong, UHF left cross pole, X right single transmit, X right ping-pong, X left single transmit, and X left ping-pong.
- Three dimensional baseline corrections for the four physical baselines: the UHF left, the UHF right, the X left, and the X right.
- Phase and amplitude corrections for all 14 distinct logical channels.
- Eight interferometric phase screens: URP, URS, XRP, XRS, ULP, ULS, XLP, and XLS.
- Yaw and pitch EGI biases for both EGIs.

Processing Mode Definitions

Processing Mode	Baseline Length(m)	Mode Name
XLS	2.6	X-Band Left Looking Single Transmit
XLP	5.2	X-Band Left Looking Ping-Pong
XRS	2.6	X-Band Right Looking Single Transmit
XRP	5.2	X-Band Right Looking Ping-Pong
URC		UHF Right Looking Cross Polarization
URP	42.4	UHF Right Looking Ping-Pong
URS	21.2	UHF Right Looking Single Transmit
ULC		UHF Left Looking Cross Polarization
ULP	42.4	UHF Left Looking Ping-Pong
ULS	21.2	UHF Left Looking Single Transmit

Expected Variation of Parameters

	Data Take	Look Direction	Band- width	Alti- tude	Ping -Pong
EGI Biases	N	N	N	?	N
Platform Position	Y	N	N	N	N
Common Range Delay	N	Y	Y	N	N
Differential Time Delay	N	Y	Y	N	Y
Baseline Correction	N	Y	?	?	N
Phase Correction	N	Y	?	?	Y
Amplitude Correction	N	Y	?	?	Y
Phase Screen	N	Y	?	?	N

Error Functions

- The baseline corrections, the time delays, and the phase delays are determined by fitting the errors in the imaged corner reflector positions using the known sensitivity. In this section we will present the sensitivities for the relevant variables.
- Here the 3-D planar earth equations will be presented. In practice, the spherical earth corrections are also applied.

Error in Platform Position

$$\frac{\partial \vec{T}}{\partial P_s} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

$$\frac{\partial \vec{T}}{\partial P_c} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \quad (2)$$

$$\frac{\partial \vec{T}}{\partial P_h} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (3)$$

P_s , P_c , and P_h are the three components of the aircraft position, \vec{P} , in the along track direction, in the across track direction, and in height, respectively. \vec{T} is the target position, ρ is the range to the target, and \hat{l}_{sch} is the look direction to the target. The three component vector in square brackets indicates the s , c , and h components.

Intuitively, an error in the aircraft position merely translates the entire scene. This is expected since $\vec{T} = \vec{P} + \rho \hat{l}_{sch}$.

Error in the Range

$$\frac{\partial \vec{T}}{\partial \rho} = \begin{bmatrix} \cos(\beta) \\ \mu \sin(\theta) \\ -\cos(\theta) \end{bmatrix} = \hat{l}_{sch} \quad (4)$$

where

$$\mu = \sqrt{1 - \left(\frac{\cos(\beta)}{\sin(\theta)} \right)^2}, \quad (5)$$

β is the angle between the aircraft velocity and the look direction, and θ is the look angle.

Error in Baseline Length

$$\frac{\partial \vec{T}}{\partial B} = \frac{\rho}{B} \left(g_{tan} + \frac{\tan(\kappa) \cos(\beta)}{g_{cos}} \right) \begin{bmatrix} 0 \\ -\cos(\theta) \\ -\mu \sin(\theta) \end{bmatrix} \quad (6)$$

where

$$g_{tan} = \frac{\cos(\alpha) \sin(\theta) \mu - \sin(\alpha) \cos(\theta)}{\sin(\alpha) \sin(\theta) \mu + \cos(\alpha) \cos(\theta)}, \quad (7)$$

$$g_{cos} = \sin(\alpha) \sin(\theta) \mu + \cos(\alpha) \cos(\theta), \quad (8)$$

α is the baseline roll angle, B is the baseline length, and κ is the baseline yaw angle.

Error in Baseline Roll Angle

$$\frac{\partial \vec{T}}{\partial \alpha} = \rho \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu \sin(\theta) \end{bmatrix} \quad (9)$$

Error in Baseline Yaw Angle

$$\frac{\partial \vec{T}}{\partial \kappa} = \rho \left(\tan(\kappa) g_{tan} + \frac{\cos(\beta)}{g_{cos}} \right) \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu \sin(\theta) \end{bmatrix} \quad (10)$$

Error in Phase

$$\frac{\partial \vec{T}}{\partial \phi} = \left(\frac{-\lambda \rho}{a 2\pi B g_{cos} \cos(\kappa)} \right) \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu \sin(\theta) \end{bmatrix} \quad (11)$$

where a is 1 or 2 for ping-pong or single transmit.

Fitting for the Corrections

$$\frac{\partial \vec{T}}{\partial \vec{P}} \Delta \vec{P} + \frac{\partial \vec{T}}{\partial \rho} \Delta \rho + \frac{\partial \vec{T}}{\partial B} \Delta B + \frac{\partial \vec{T}}{\partial \alpha} \Delta \alpha + \frac{\partial \vec{T}}{\partial \kappa} \Delta \kappa + \frac{\partial \vec{T}}{\partial \phi} \Delta \phi = \Delta \vec{T} \quad (12)$$

We know the derivatives, and we can measure the target position error $\Delta \vec{T}$ for each target. Therefore we can solve the Least Squares technique for the error in the platform position $\Delta \vec{P}$, the error in the range $\Delta \rho$, the error in the baseline length ΔB , the error in the baseline roll angle $\Delta \alpha$, the error in the baseline yaw angle $\Delta \kappa$, and the error in the phase $\Delta \phi$. We use Singular Value Decomposition to evaluate the actual errors.

Slant Plane Corrections

The error of the range of a target is given by

$$\frac{\partial \rho}{\partial P_s} \Delta P_s + \frac{\partial \rho}{\partial P_c} \Delta P_c + \frac{\partial \rho}{\partial P_h} \Delta P_h + \frac{\partial \rho}{\partial \tau} \Delta \tau = \Delta \rho, \quad (13)$$

where

$$\begin{aligned} \frac{\partial \rho}{\partial P_s} &= \cos(\beta), & \frac{\partial \rho}{\partial P_c} &= \mu \sin(\theta), \\ \frac{\partial \rho}{\partial P_h} &= -\cos(\theta), & \frac{\partial \rho}{\partial \tau} &= 1, \end{aligned} \quad (14)$$

and τ is the common range delay. The location error in range of each target is measured, and equation (13) is solved using singular value decomposition to determine the platform position errors and range errors.

Combining Data from Multiple Passes

There are three reasons to combine data from multiple data takes to estimate calibration parameters:

- The increased number of observations can reduce the statistical errors in the estimated quantities, and
- the mean platform position error over many data takes should be zero. If a sufficiently large number of data takes were considered, it might not be necessary to fit for the platform position error for each data take at all.
- A more reliable estimate of the baseline yaw angle can be determined if data with differing squint angles can be synthesized.

The concern is that you not degrade the calibration parameter estimates by averaging over cases that really are distinct.

Multiple Pass Slant Plane Corrections

The error of the range of target i imaged on data take k in mode j is given by

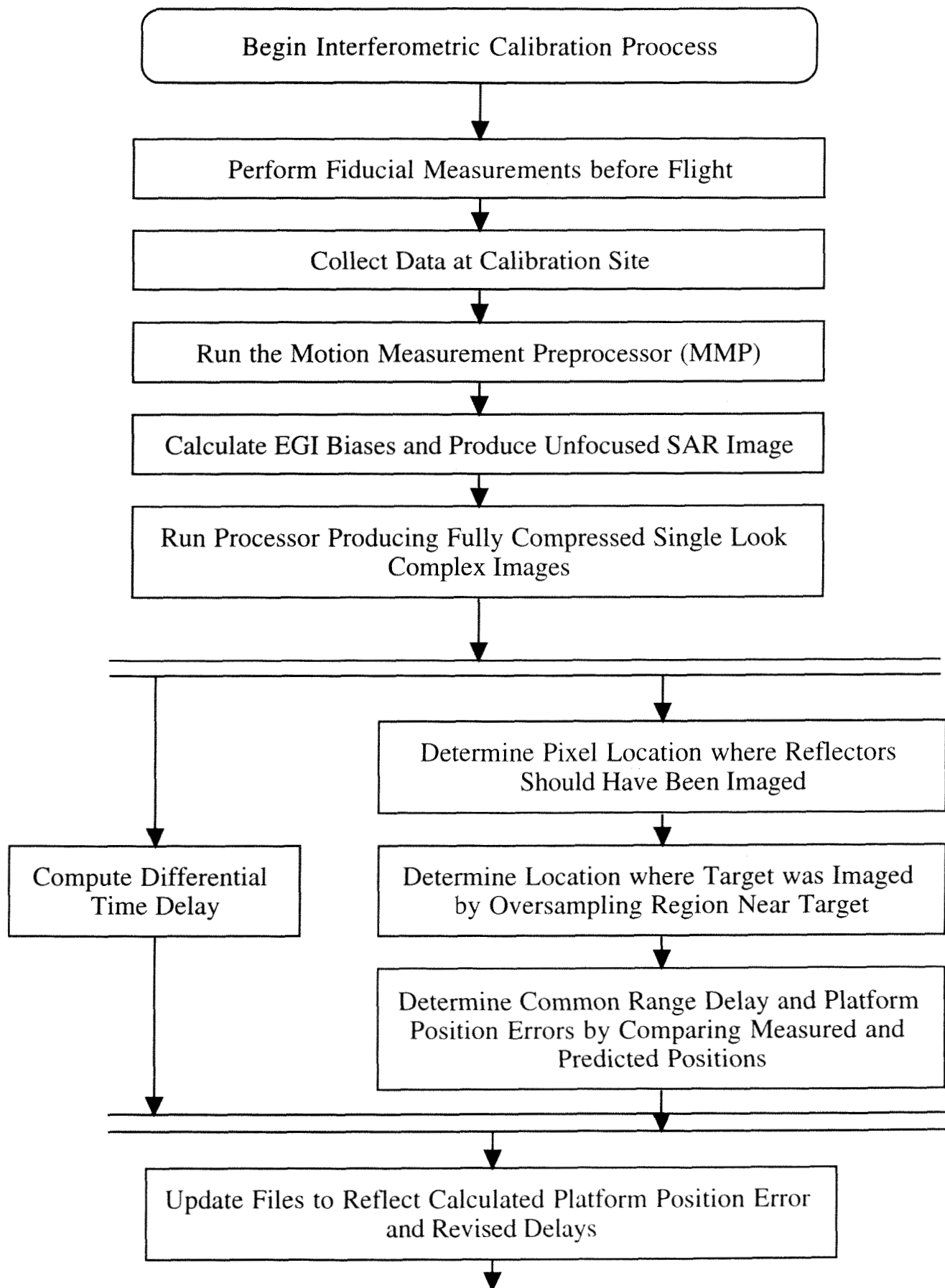
$$\frac{\partial \rho}{\partial P_{sk}} \Delta P_{sk} + \frac{\partial \rho}{\partial P_{ck}} \Delta P_{ck} + \frac{\partial \rho}{\partial P_{hk}} \Delta P_{hk} + \frac{\partial \rho}{\partial \tau_j} \Delta \tau_j = \Delta \rho_i. \quad (15)$$

The full equation to be solved when combining X-band data from both Left and Right looking modes from K data takes is:

$$\begin{aligned} & + \frac{\partial \rho}{\partial P_{s1}} \Delta P_{s1} & + \frac{\partial \rho}{\partial P_{c1}} \Delta P_{c1} & + \frac{\partial \rho}{\partial P_{h1}} \Delta P_{h1} \\ & + \frac{\partial \rho}{\partial P_{s2}} \Delta P_{s2} & + \frac{\partial \rho}{\partial P_{c2}} \Delta P_{c2} & + \frac{\partial \rho}{\partial P_{h2}} \Delta P_{h2} \\ & + \frac{\partial \rho}{\partial P_{s3}} \Delta P_{s3} & + \frac{\partial \rho}{\partial P_{c3}} \Delta P_{c3} & + \frac{\partial \rho}{\partial P_{h3}} \Delta P_{h3} \\ & \dots & & \\ & + \frac{\partial \rho}{\partial P_{sK}} \Delta P_{sK} & + \frac{\partial \rho}{\partial P_{cK}} \Delta P_{cK} & + \frac{\partial \rho}{\partial P_{hK}} \Delta P_{hK} \\ & + \frac{\partial \rho}{\partial \tau_L} \Delta \tau_L & + \frac{\partial \rho}{\partial \tau_R} \Delta \tau_R & = \Delta \rho \end{aligned} \quad (16)$$

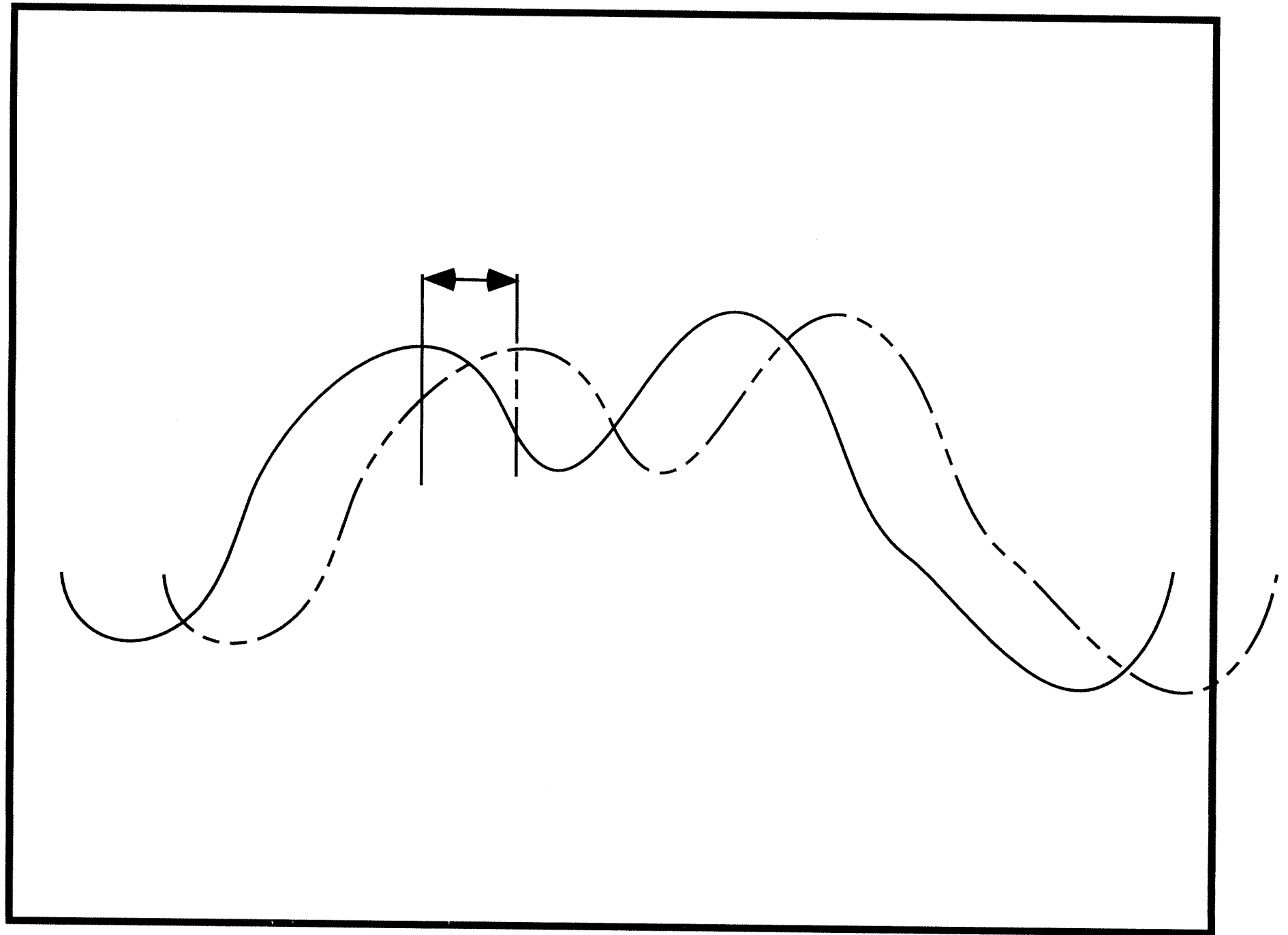
Computing Common Range Delay from Multiple Passes

- Calculate the vector of observations, $O_i = (\rho_{im} - \rho_{is})$, where i is the reflector number, ρ_m is the measured range of the target, and ρ_s is the surveyed position of the reflector.
- Calculate the derivatives of the range with respect to the common range delay, $\frac{\partial \rho_i}{\partial \tau_j}$, and the range with respect to the platform position, $\frac{\partial \rho_i}{\partial \vec{P}_k}$ for each corner reflector for each data take, k , for each mode, j .
- Solve for the unknowns. For K data takes, there will be $3K+2$ unknowns for X-Band GeoSAR data. With 12 corner reflectors on one side and 1 on the other, there should be $13K$ observations.



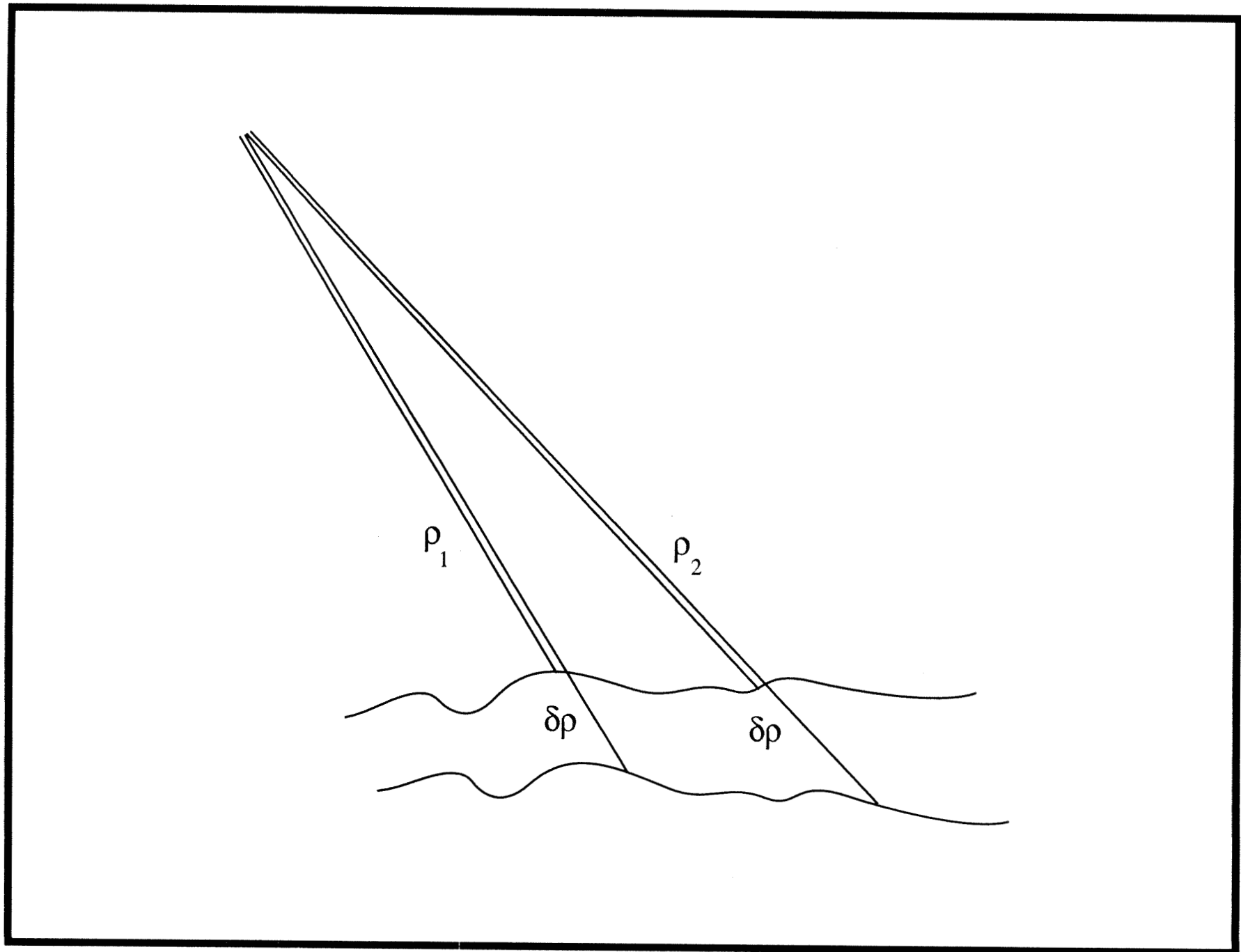
Differential Time Delay

- The differential time delay is the difference between the time delays for two channels.
- The differential time delay can be determined by examining the time difference when two channels view common objects in the slant plane image. This method is accurate to about 0.2 pixels. The accuracy is limited by the ability to resolve the position of the target to a fraction of a pixel and by the number of targets to average.
- Alternately the differential time delay can be determined by cross correlating the slant plane images of the two channels. This second method is accurate to about 0.05 pixels. Cross correlations can be done throughout the image; no radar identifiable targets are required.



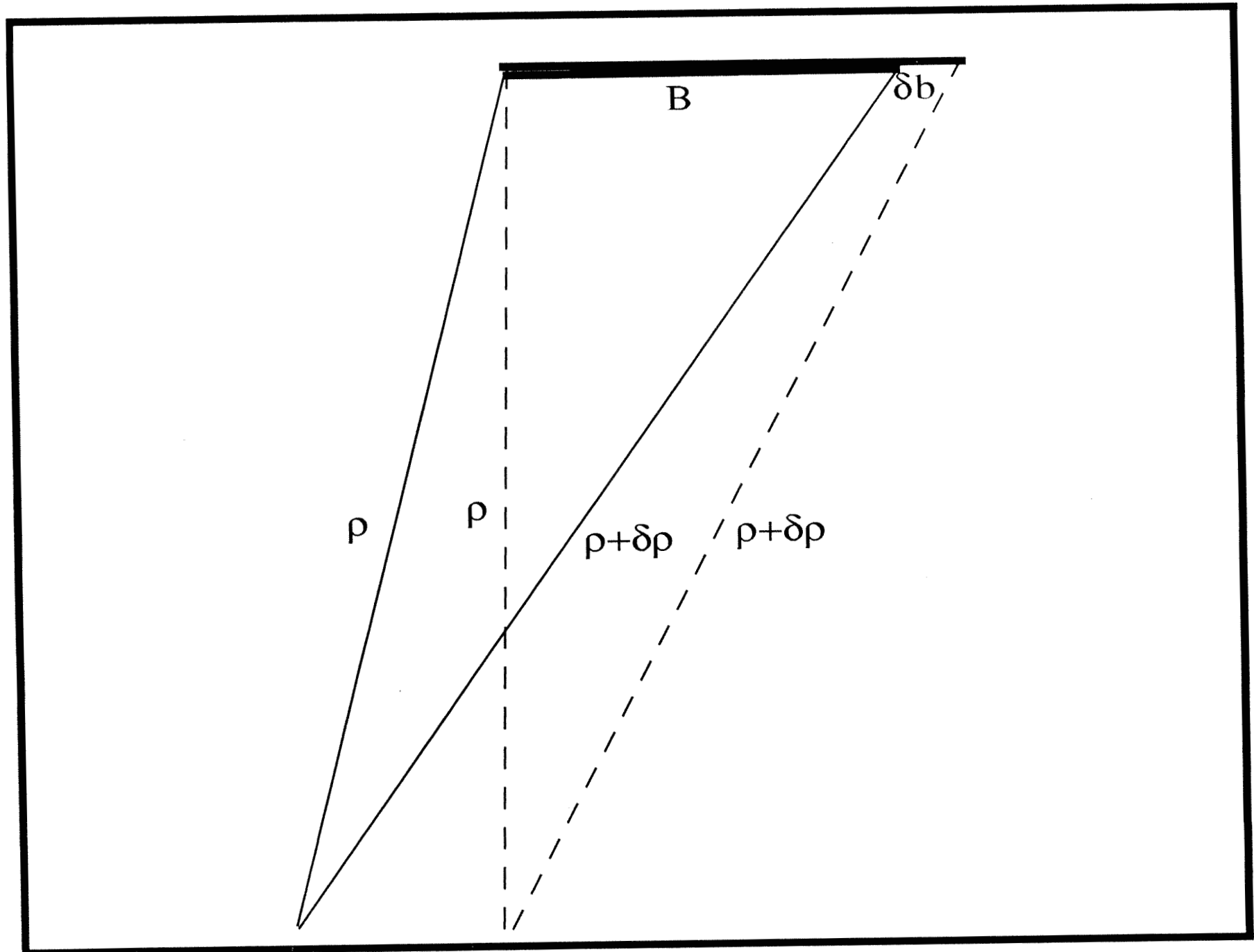
Common Range Delay

- The common range delay is the time delay for one of the two interferometric channels identified as the reference.
- The common range delay can be determined by examining the location in the slant plane image where a recognizable target of known location was imaged. This method is accurate to about 0.2 pixels. The accuracy is limited by the ability to resolve the position of the target to a fraction of a pixel and by the number of targets to average and the uncertainty in the aircraft position.
- Since the differential time delay can be calibrated more accurately than the common range delay, the calibration procedure is to calculate as many time delays as possible as differential time delays and as few as possible using the common range delay procedure.



Baseline Corrections

- The locations and orientations of the EGI's, the GPS, and the antennas have been precisely surveyed with the plane on the ground. However, for interferometry we require more accurate values.
- Since the mechanical baseline is actively measured by the LBMS, the baseline calibration parameters consists of calculating a constant offset which corresponds to a difference between the electrical phase centers of the antennas and the mechanical center.
- The baseline corrections can be determined by fitting the errors in the imaged corner reflector positions using the known sensitivities. Baseline corrections can be measured to fractions of a centimeter.

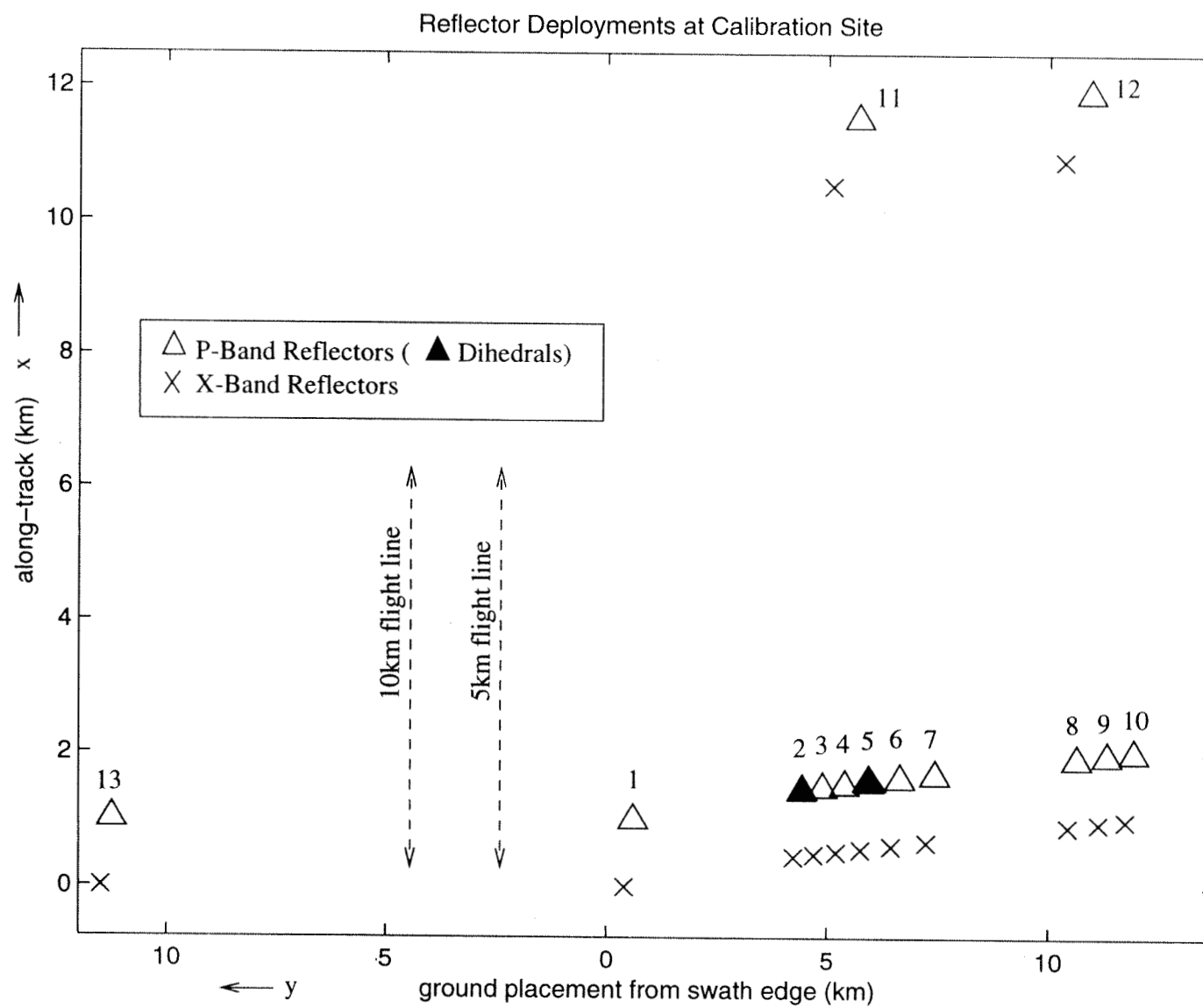


Phase Screen Determination

- The phase screen is a final correction applied to the data to remove the effects of multipath and/or switch leakage in the data. The phase screen is a phase offset calculated as a function of absolute phase.
- The phase screen is calculated by measuring the difference between the measured heights and reference heights from a high resolution DEM over a scene. Height differences with the same look angle over the scene are averaged together. These height differences are then multiplied by the derivative of phase as a function of height to calculate a phase offset. The offsets are then used to fit for a Chebychev polynomial.

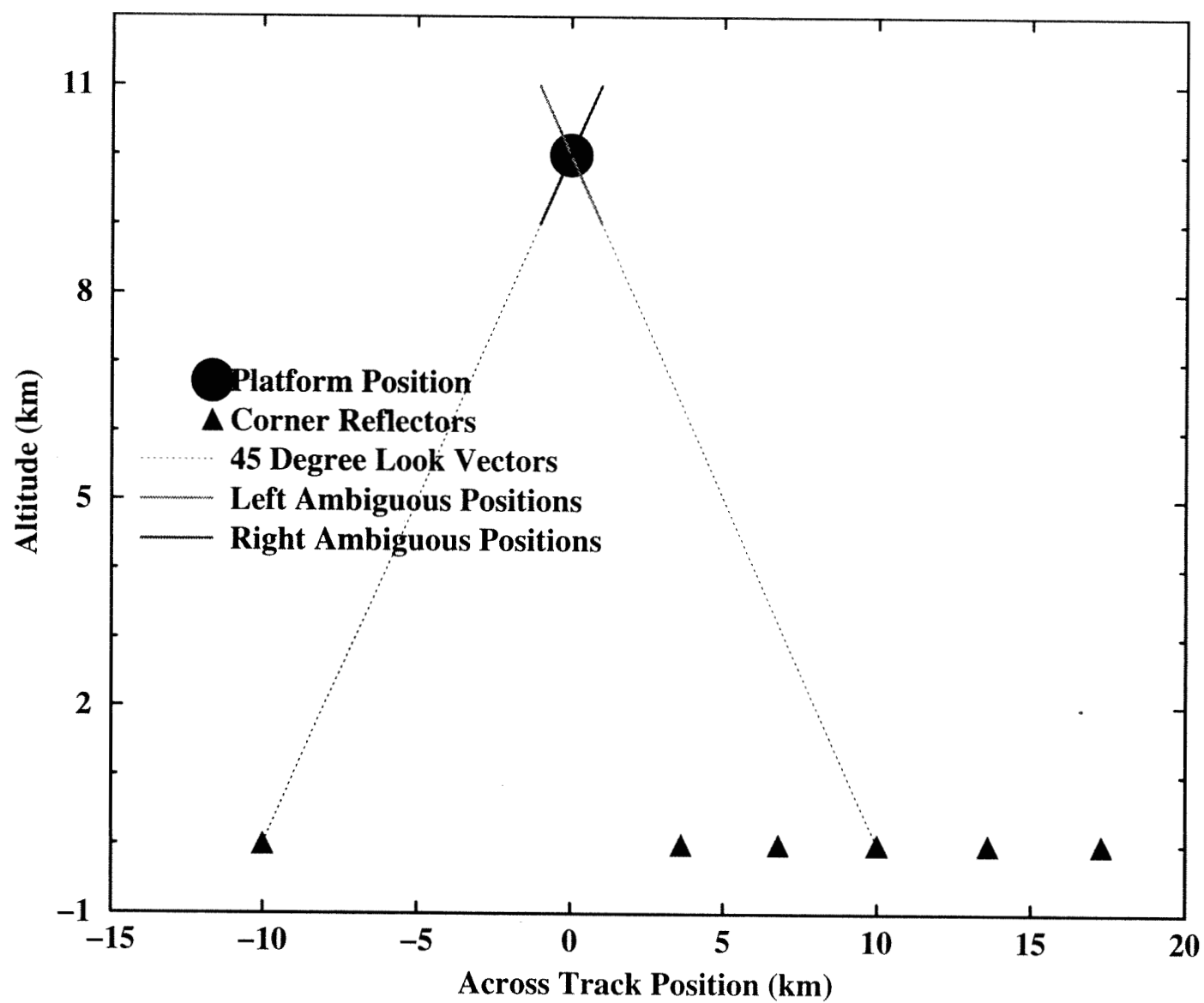
Principle Elements of Calibration Site

- DEM covering full swath width and at least one synthetic aperture length along track.
- Corner reflectors distributed in range across the swath.
- Two corner reflectors displaced along track from the main array to assist in corresterring the radar DEM to reference DEM in the phase screen process.
- One corner reflector in the swath of the opposite look direction to assist in determining the common range delay and the aircraft position error.
- A few dihedrals for use calibrating the cross-pole channel at P-Band.



Dual Sided Operation

- GeoSAR system is dual-sided, simultaneously imaging swaths to both the left and right of the aircraft. Each side images look angles from approximately 20° to 60° .
- In single sided imaging, the common range delay determination algorithm tends to trade off errors in the common range delay with errors in the platform position in a plane defined by the 45° look vector and the along track velocity.
- By imaging corner reflectors on both sides of the aircraft, this ambiguity can dramatically reduced.
- Assuming that there are no GPS constellation changes, the platform position error is approximately constant over the minute that it takes to image the corner reflectors during a data take.



Conclusions and Future Work

- With the engineering check out flight data available thus far, the calibration procedure is working well.
- We look forward to fully testing the calibration software when LBMS and P-Band data become available.

